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The operational characteristics of an engineering model SPT-140 Hall thruster of a size and type under consideration for spacecraft insertion and control were evaluated through a cooperative agreement between the Boeing Commercial Space Company and the NASA Lewis Research Center. Tests of the SPT-140 engine were conducted using commercially available laboratory power supplies and a laboratory model xenon feed system. Stable operation was obtained over a range of input powers from 0.6 to 5 kilowatts. Specific impulses between 1200 and 1950 seconds were measured. Thruster efficiencies increased from 0.32 to 0.59 over this range. The effect of facility pressure on thruster performance was investigated and found to be significant with regard to specific impulse and thruster efficiency at pressures on the order of 10-5 Torr. These tests demonstrated the viability of the SPT-140 as a candidate for insertion and control of next generation satellites.

Introduction

Hall effect thrusters, or thrusters with closed electron drift, have found widespread application on Russian spacecraft dating back to the 1970's.[1] Since the early 1990's there has been considerable interest by other government and commercial spacecraft manufacturers in using this technology aboard next generation spacecraft. The focus of that interest has been the development of 1.5 kW systems optimized for the North-South stationkeeping (NSSK) of commercial geosynchronous communication satellites.[2-4] With the anticipated growth in power available on board future spacecraft, higher power Hall systems are being considered for both orbit insertion and on-orbit operation.[5] Activities related to interest in high power Hall thrusters for these purposes include the Ballistic Missile Defense Organization (BMDO) sponsored investigation of the 7 kW anode layer thruster produced by TsNIIMASH[6] and a flight demonstration of a 4.5 kW Hall thruster system aboard a Russian geostationary communication satellite scheduled to be launched in 1999.[7]

The Boeing Commercial Space Company (BCSC) has a significant interest in Hall thrusters for on-orbit propulsion. Based on this interest, a cooperative program was undertaken with the NASA Lewis Research Center (NASA LeRC) to evaluate an SPT-140 Hall thruster. The SPT-140, manufactured by Fakel Enterprises in Kaliningrad, Russia and provided for test by International Space Technology, Inc. (ISTI) maybe a candidate for orbit insertion and repositioning of future spacecraft. The objective of this investigation was to measure the operating characteristics and performance of an engineering model SPT-140 Hall thruster over the full range of recommended operating conditions. Two different sized hollow cathodes were used to operate the engine over the range of desired discharge currents. The effect of facility pressure on performance was also examined.

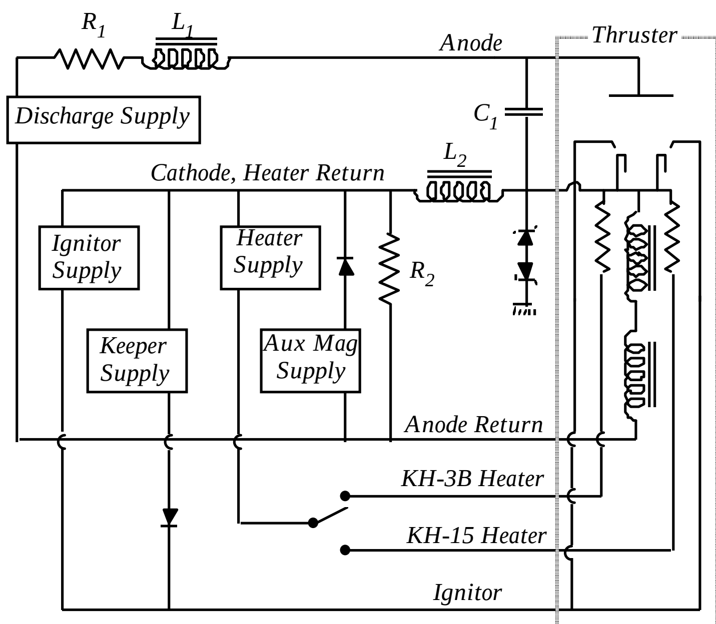
Apparatus and Procedure

The engineering model SPT-140 used in these tests is shown in Figure 1. The thruster was operated at powers between 0.6 and 5 kilowatts. This was accomplished by providing anode xenon flow rates ranging from 2 to 16 mg/s at discharge voltages between 250 and 400 Volts. Two different cathodes were employed in order to cover the entire range of discharge currents tested. A low current cathode, designated the KH-3B, was used at discharge currents between 2 and 5 Amperes and a higher current cathode, designated the KH-15, was used for currents between 2 and 15 Amperes. The flow rates for the KH-3B and the KH-15 were 0.5 and 0.7 mg/s of xenon respectively. Both these cathodes had lanthanum hexaboride emitters and needed to be preheated with a resistive heater prior to operation. Neither cathode was optimized for operation with this engine.

Figure 1: Picture of the SPT-140. The KH-15 cathode is on the right, the KH-3B is on the left.

The thrust produced by the SPT-140 was measured using an inverted pendulum design thrust stand which has been used in previous evaluations of Hall effect thrusters.[8,9] Data were taken in two different space simulation testbeds at NASA LeRC. Preliminary data were taken in a medium sized cylindrical chamber (Tank 8) with dimension of 5m in length by 1.5m in diameter. Background pressures in the Tank 8 tests ranged from 3 to 8×10^{-5} Torr dependent on the anode flow. This corresponded to xenon pumping speed of approximately 20,000 liters per second. The remainder of the tests were conducted in large space simulation (Tank 5) with a xenon pumping speed of approximately 500,000 liters per second. The dimensions of Tank 5, which is also cylindrical, are 19m in length by 5m in diameter. For the tests conducted in this facility the background pressures were between 2 and 4×10^{-6} Torr of xenon during thruster operation.

A schematic of the electrical configuration used is shown in Figure 2. Commercially available power supplies were used to run the discharge, cathode heater, magnets, cathode ignitor and cathode keeper. The discharge supply was a constant voltage source with a in-line ballast resistor. An ouput filter was used to minimize the effects of potential current oscillations on the various laboratory supplies. Two output filter configurations were used. These differed by the magnitude of the capacitor between the anode and cathode. The value of this capacitor was 6 microFarads for the tests conducted in Tank 8 and 100 microFarads for the tests run in Tank 5. In neither case was the output filter optimized. The thruster electromagnets were energized in series with the thruster discharge. The entire electrical system was allowed to float relative to ground with the exception of the cathode. The cathode was clamped to within 50 Volts of facility ground by back to back zener diodes to prevent unanticipated voltage excursions during start-up. Typical cathode to ground voltages were on the order of -20 Volts.



R_1 = 0-30 Ω, R_2 = 1-6 Ω, C_1 = 6 or 100 μF, L_1 = L_1 = 350 mH

Figure 2: Electrical schematic for SPT-140 testing.

The thruster was operated on commercially available research grade xenon (purity better than 99.9995%). A laboratory model feed system which incorporated commercially available mass flow controllers was used to provide the desired flow rate to the anode and cathode. These flow meters were calibrated before and after each series of tests. Uncertainties in mass flow rate measurements were estimated to be ±2%. The thrust stand was calibrated in-situ using three weights with a mass of approximately 0.010 kilograms each. The uncertainty in the thrust measurements, primarily due to zero drift, was estimated to be ±1.5%.

Results and Discussions

To evaluate the operational characteristics of the SPT-140 thruster, a number of tests were performed. The first series of tests were conducted in the smaller vacuum chamber at vacuum pressures on the order of 10^{-5} Torr using both the KH-3B and the KH-15 cathodes. Subsequent tests were conducted in a higher fidelity space simulation chamber at vacuum pressures on the order of 10^{-6}. For these tests only the KH-15 cathode was used. All data taken in the course of testing, including the background pressure for each data point, are presented in tabular form in the Appendix.

Figure 3 depicts the variation of thrust with thruster input power for all the data collected during this investigation with discharge voltages between 280 and 350 Volts. As can be seen, the variation was essentially linear with no effect of background pressure. Data scatter was attributed to differences in discharge voltage and variations in magnet current. At a given anode flow rate and discharge voltage, variation in magnet current over the range tested did have a secondary effect on discharge current, but did not have any significant effect on thrust. The effect of magnet current on discharge current has been demonstrated previously[8] and was used to find the optimal operating point with respect to magnet current. Because the thrust was not significantly affected by changes in magnet current, the magnet current which resulted in the lowest discharge current , and therefore power, for a given discharge voltage and anode flow rate, optimized the performance.

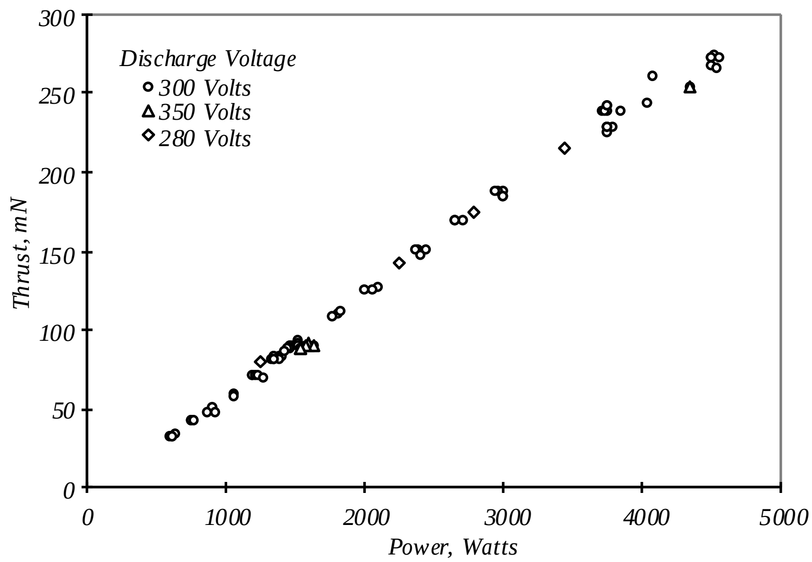


Figure 3: Thrust versus input power for the SPT-140 at different discharge voltages

The discharge current obtained at a given anode flow rate was dependent on the background pressure. Figure 4 displays the variation in discharge current as a function of anode flow rate for the data taken in Tank 8 and in Tank 5. The background pressure in each vacuum tank changed linearly as a function of anode flow rate and therefore is not explicitly indicated on this figure. However, as an indication of the pressure for each test, the pressure in Tank 8 ranged from $1x10^{-5}$ Torr to $8x10^{-5}$ Torr as the anode flow rate increased from 2 to 13.5 mg/s. In Tank 5, the pressure changed from less than $2x10^{-6}$ Torr to 4 $x10^{-6}$ Torr as the anode flow rate was increased from 5 to 16 mg/s.

The data clearly indicate that the anode flow rate required to provide a given discharge current was nearly 10 % higher at the lower background pressure. This effect, which has been demonstrated previously,[10] has only been qualitatively explained. At the higher background pressure background xenon diffused into the discharge chamber where it was subsequently ionized and accelerated by the engine. The ingested background gas provided a higher effective anode flow rate than was being provided via the xenon feed system, where the anode flow rate was measured. Kinetic flow calculations of the flux of background gas into the discharge chamber based on the geometry of the thruster and the measured background pressure underpredicted this a substantial amount. A neutral xenon pressure near the thruster higher than the pressure measured near the tank wall could account for the difference. One source of neutral xenon near the thruster was the external hollow cathode which was in close proximity to the discharge chamber. Another potential source for the discrepancy between the kinetic calculations and experiment was an effective entrainment area larger than the geometic area of the discharge chamber used in the calculation.

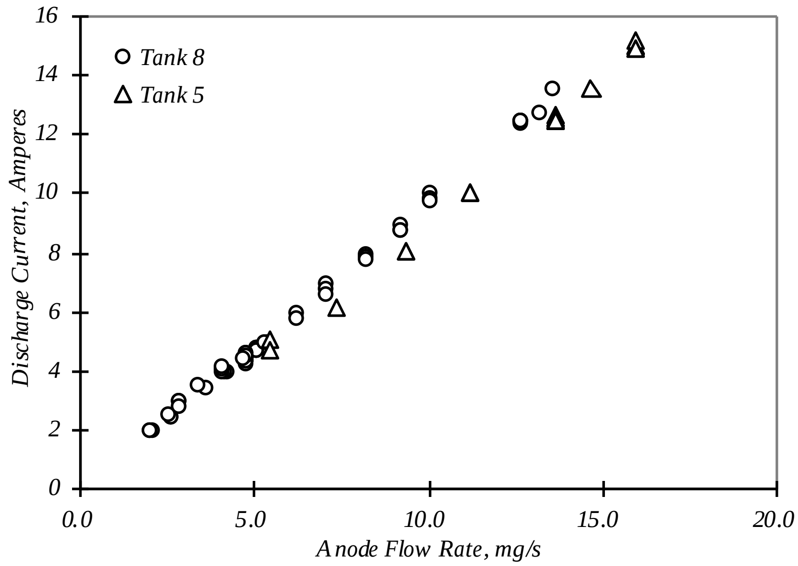


Figure 4: Discharge current versus anode flow rate measured in two different facilities. The data taken in Tank 8 were at a background pressure on the order of 10^{-5} Torr and the data taken in Tank 5 were at a pressure on the order of 10^{-6} Torr.

Based on the measured thrust and xenon flow rate, specific impulse values were calculated and are plotted as a function of thruster power in Figure 5. The specific impulses ranged from a low of 1240 seconds at 620 Watts and 300 Volts to a high of 1950 seconds at a 400 Volt, 5 kilowatt operating condition. In general the specific impulse increased with increasing power. The specific impulses measured at background pressures on the order of 10^{-6} Torr were typically 200 seconds lower than those measured at pressures on the order of 10^{-5} Torr for given power. This was attributed to the increased anode flow required at the lower facility pressure to obtain the desired discharge current. Below 1.5 kilowatts it was possible to operate the SPT-140 on either the KH-3B cathode or the KH-15 cathode. Because the KH-15 cathode was intended for higher current operation, it was less efficient than the KH-3B at these power levels, that is, the KH-15 required 40 % more flow than the KH-3B resulting in lower specific impulse for those points.

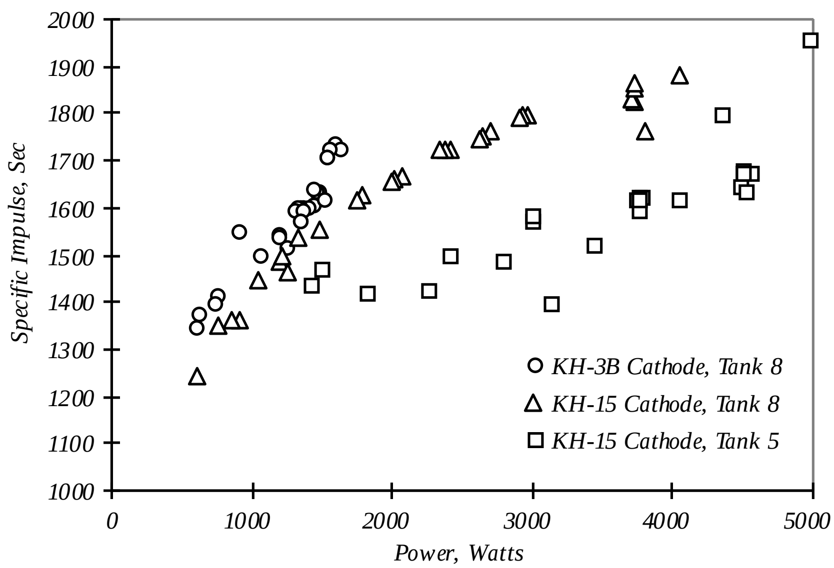


Figure 5: Specific Impulse versus Thruster Power

Finally, thruster efficiency was determined based on the thrust, xenon flow rate, and input power as a function of specific impulse. These data are shown in Figure 6. There appears to be a linear increase in efficiency with specific impulse. The increase in efficiency with specific impulse for the data collected in Tank 5 was much less than that measured in Tank 8. This was again attributed to the higher anode flow rate requirements in Tank 5. Of special note are the two highest specific impulse points measured using the KH-15 cathode in Tank 5. These were obtained by increasing the discharge voltage to 350 and then 400 Volts. While this had a positive effect on specific impulse and efficiency, it was believed that associated with these operating points were increased discharge chamber erosion and therefore reduced thruster lifetime.

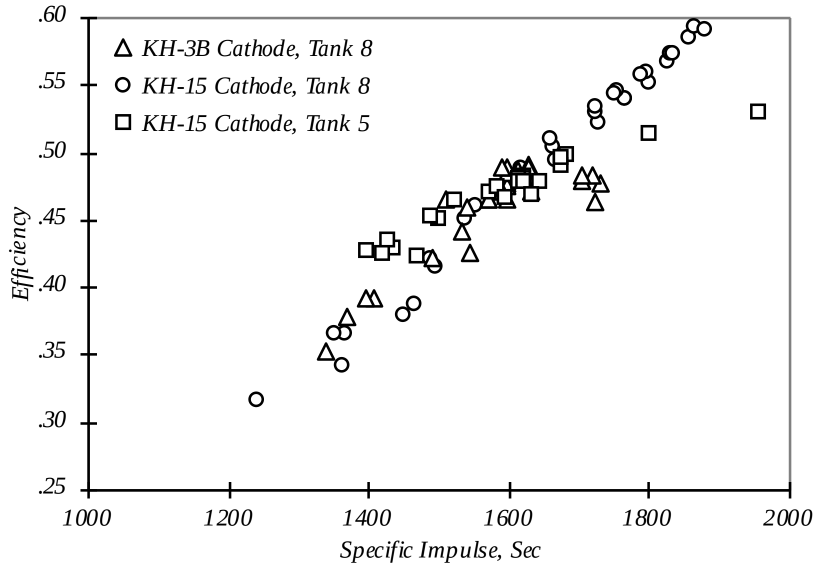


Figure 6: Thruster efficiency versus specific impulse.

Conclusions

The operational characteristics of an engineering model SPT-140 Hall thruster was experimentally evaluated in two different test facilities under a copperative BCSC/NASA LeRC program. The engine ran reliably at powers ranging from 0.6 to 5 kW, produced specific impulses between 1200 and 1950 seconds, and provided thrust at levels up to 276 mN. The effect of facility pressure on measured performance was found to be significant. Specific impulses determined based on measurements taken at vacuum pressures of 10^{-5} Torr overpredicted the specific impulse measured at pressures an order of magnitude lower by as much as 250 seconds. This was attributed to higher anode flow requirements for a given discharge current at lower vacuum pressures. The performance of the SPT-140 demonstrated during this investigation confirm the viability of this device as a candidate for orbit insertion and control of next generation satellites.

Acknowledgment

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Appendix

Table I: Data taken in Tank 8 with KH-3B cathode.

anode flow	cathode flow	total flow	current	voltage	aux mag current	Total Power	Thrust	Isp	efficiency	Pressure
mg/s	mg/s	mg/s	Amperes	volts	Amperes	Watts	mN	sec		torr
5.10	0.50	5.61	4.8	304	3.0	1462	89.6	1631	0.49	3.2E-5
5.10	0.50	5.61	4.9	304	3.0	1477	89.6	1631	0.48	3.2E-5
5.10	0.50	5.61	4.8	304	3.0	1471	89.6	1631	0.49	3.2E-5
5.10	0.50	5.61	4.8	304	3.0	1450	88.0	1602	0.48	3.2E-5
5.10	0.50	5.61	4.8	304	3.0	1453	88.0	1602	0.48	3.2E-5
5.10	0.50	5.61	4.8	304	3.0	1448	88.2	1604	0.48	3.2E-5
5.36	0.50	5.87	5.0	304	3.0	1517	92.9	1616	0.48	3.3E-5
4.79	0.50	5.29	4.5	305	3.0	1375	82.9	1600	0.47	3.0E-5
4.79	0.50	5.29	4.6	305	2.6	1404	82.9	1600	0.46	3.0E-5
4.79	0.50	5.29	4.4	305	3.5	1346	82.9	1600	0.48	3.0E-5
4.79	0.50	5.29	4.4	305	4.0	1333	82.9	1600	0.49	3.0E-5
4.79	0.50	5.29	4.3	305	4.3	1319	82.5	1592	0.49	3.0E-5
4.79	0.50	5.29	4.5	305	3.0	1375	82.6	1594	0.47	3.0E-5
4.79	0.50	5.29	4.5	280	3.0	1256	78.4	1513	0.46	3.0E-5
4.79	0.50	5.29	4.5	320	3.0	1446	84.8	1637	0.47	3.0E-5
4.79	0.50	5.29	4.6	350	3.0	1606	89.9	1735	0.48	3.0E-5
4.79	0.50	5.29	4.7	350	2.5	1640	89.4	1725	0.46	3.0E-5
4.79	0.50	5.29	4.5	350	3.5	1568	89.3	1724	0.48	3.0E-5
4.79	0.50	5.29	4.4	350	4.0	1545	88.4	1706	0.48	3.0E-5
4.79	0.50	5.29	4.4	350	4.3	1535	88.4	1706	0.48	3.0E-5
4.27	0.50	4.77	4.0	300	3.5	1192	72.1	1543	0.46	2.6E-5
3.64	0.50	4.14	3.5	302	3.0	1060	60.7	1495	0.42	2.3E-5
2.84	0.50	3.34	3.0	304	3.0	906	50.6	1546	0.42	1.8E-5
2.58	0.50	3.08	2.5	305	3.0	753	42.6	1411	0.39	1.6E-5
2.58	0.50	3.08	2.4	305	3.5	742	42.2	1398	0.39	1.6E-5
2.11	0.50	2.61	2.0	306	3.0	627	35.1	1373	0.38	1.3E-5
1.98	0.50	2.48	2.0	307	2.5	610	32.6	1342	0.35	1.2E-5
4.16	0.50	4.66	4.0	301	3.0	1201	70.1	1534	0.44	2.6E-5
4.79	0.50	5.29	4.5	299	3.0	1354	81.5	1573	0.46	3.0E-5
4.79	0.50	5.29	4.5	299	3.0	1354	81.5	1573	0.46	3.0E-5

Table II: Data taken in Tank 8 with KH-15 cathode.

anode flow	cathode flow	total flow	current	voltage	aux mag current	Total Power	Thrust	Isp	efficiency	Pressure
mg/s	mg/s	mg/s	Amperes	volts	Amperes	Watts	mN	sec		torr
13.14	0.70	13.84	12.8	300	0.0	3828	239.4	1765	0.54	8.1E-5
12.62	0.70	13.32	12.5	300	0.0	3750	238.2	1825	0.57	7.8E-5
12.62	0.70	13.32	12.4	300	0.0	3720	238.6	1828	0.57	7.8E-5
12.62	0.70	13.32	12.4	300	0.0	3732	239.0	1831	0.57	7.8E-5
12.62	0.70	13.32	12.5	301	0.0	3750	242.0	1854	0.59	7.8E-5
12.62	0.70	13.32	12.5	300	1.0	3738	243.0	1862	0.59	7.8E-5
9.98	0.70	10.68	10.0	300	0.0	2994	188.0	1797	0.55	6.2E-5
9.98	0.70	10.68	9.8	300	1.0	2949	187.8	1795	0.56	6.2E-5
9.98	0.70	10.68	9.8	301	2.0	2936	187.2	1789	0.56	6.2E-5
9.15	0.70	9.85	9.0	303	1.0	2721	170.3	1764	0.54	5.7E-5
9.15	0.70	9.85	8.9	300	2.0	2656	169.2	1752	0.55	5.7E-5
9.15	0.70	9.85	8.8	300	2.5	2651	168.7	1747	0.54	5.7E-5
8.21	0.70	8.91	8.0	303	1.0	2436	150.6	1725	0.52	5.1E-5
8.21	0.70	8.91	7.9	303	2.0	2395	150.4	1723	0.53	5.1E-5
8.21	0.70	8.91	7.8	303	3.0	2366	150.2	1721	0.54	5.1E-5
7.08	0.70	7.78	7.0	300	1.0	2097	127.0	1667	0.49	4.4E-5
7.08	0.70	7.78	6.8	301	2.0	2042	126.7	1663	0.51	4.4E-5
7.08	0.70	7.78	6.7	301	3.0	2010	126.3	1658	0.51	4.4E-5
6.20	0.70	6.90	6.0	303	2.0	1810	110.1	1628	0.49	3.8E-5
6.20	0.70	6.90	5.8	303	3.0	1766	109.3	1616	0.49	3.8E-5
5.29	0.70	5.99	5.0	300	3.0	1506	91.2	1553	0.46	3.3E-5
4.69	0.70	5.39	4.5	301	3.0	1351	81.1	1535	0.45	2.9E-5
4.11	0.70	4.81	4.0	303	3.0	1209	70.1	1486	0.42	2.5E-5
4.11	0.70	4.81	4.1	303	2.5	1238	70.5	1495	0.42	2.5E-5
4.11	0.70	4.81	4.2	302	2.0	1272	69.0	1463	0.39	2.5E-5
3.35	0.70	4.05	3.5	304	2.0	1068	57.4	1448	0.38	2.1E-5
2.86	0.70	3.56	3.0	305	2.0	925	47.5	1361	0.34	1.8E-5
2.86	0.70	3.56	2.8	306	3.0	866	47.6	1363	0.37	1.8E-5
2.56	0.70	3.26	2.5	307	3.0	779	43.1	1351	0.37	1.6E-5
1.97	0.70	2.67	2.0	308	3.0	619	32.4	1240	0.32	1.2E-5
13.52	0.70	14.21	13.5	301	0.0	4067	261.7	1879	0.59	8.4E-5

Table III: Data taken in Tank 5 with KH-15 cathode.

anode flow	cathode flow	total flow	current	voltage	aux mag current	Power	Thrust	Isp	efficiency	Tank P
mg/s	mg/s	mg/s	Amperes	volts	Amperes	Watts	mN	sec		Torr
5.49	0.70	6.19	5.0	303	3.0	1509	89.0	1468	0.42	1.8E-6
5.49	0.70	6.19	4.6	306	5.0	1421	87.0	1435	0.43	1.8E-6
7.35	0.70	8.05	6.1	300	5.0	1828	112.0	1420	0.43	1.9E-6
9.39	0.70	10.09	8.0	281	5.0	2258	141.0	1426	0.44	2.5E-6
9.39	0.70	10.09	8.0	300	5.0	2407	148.0	1497	0.45	2.5E-6
11.25	0.70	11.95	10.0	280	5.0	2798	174.0	1486	0.45	3.1E-6
11.25	0.70	11.95	10.0	301	5.0	3006	184.0	1572	0.47	3.1E-6
11.25	0.70	11.95	10.0	300	2.5	3007	185.0	1580	0.48	3.1E-6
13.72	0.70	14.42	12.5	276	2.5	3445	215.0	1521	0.47	3.8E-6
13.72	0.70	14.42	12.5	301	2.5	3758	229.0	1620	0.48	3.8E-6
13.72	0.70	14.42	12.7	299	0.0	3779	229.0	1620	0.48	3.8E-6
13.72	0.70	14.42	12.5	299	4.9	3758	225.0	1592	0.47	3.8E-6
13.72	0.70	14.42	12.5	300	2.5	3747	228.0	1613	0.48	3.8E-6
13.72	0.70	14.42	12.4	350	2.5	4349	254.0	1797	0.51	3.8E-6
13.72	0.70	14.42	12.5	400	2.5	4982	276.0	1953	0.53	3.8E-6
13.72	0.70	14.42	12.5	300	2.5	3749	228.0	1613	0.48	3.8E-6
13.72	0.70	14.42	12.6	250	2.5	3138	197.0	1394	0.43	3.8E-6
13.72	0.70	14.42	12.5	301	2.5	3757	228.0	1613	0.48	3.8E-6
14.68	0.70	15.38	13.5	298	2.5	4041	244.0	1619	0.48	4.1E-6
15.95	0.70	16.65	15.0	300	2.5	4495	268.0	1642	0.48	4.4E-6
15.95	0.70	16.65	15.0	301	5.0	4532	266.0	1630	0.47	4.4E-6
15.95	0.70	16.65	14.9	302	0.0	4503	273.0	1673	0.50	4.4E-6
15.95	0.70	16.65	15.0	301	-1.1	4509	274.0	1679	0.50	4.4E-6
15.95	0.70	16.65	15.2	300	-2.0	4558	273.0	1673	0.49	4.4E-6
15.95	0.70	16.65	14.9	302	0.0	4504	273.0	1673	0.50	4.4E-6

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13. ABSTRACT ***(Maximum 200 words)***

The operational characteristics of an engineering model SPT–140 Hall thruster of a size and type under consideration for spacecraft insertion and control were evaluated through a cooperative agreement between the Boeing Commercial Space Company and the NASA Lewis Research Center. Tests of the SPT–140 engine were conducted using commercially available laboratory power supplies and a laboratory model xenon feed system. Stable operation was obtained over a range of input powers from 0.6 to 5 kilowatts. Specific impulses between 1200 and 1950 seconds were measured. Thruster efficiencies increased from 0.32 to 0.59 over this range. The effect of facility pressure on thruster performance was investigated and found to be significant with regard to specific impulse and thruster efficiency at pressures on the order of 10^{-5} Torr. These tests demonstrated the viability of the SPT–140 as a candidate for insertion and control of next generation satellites.

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